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Jet Shapes in pp and PbPb collisions in the CMS Experiment

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Abstract

Jet shape measurements are important for many applications. When measured in pp collisions they can be used to constrain generator and showering settings. When measured in PbPb collisions they can be used to probe for distortions from interactions with the hot and dense medium. Fully unfolded jet shape measurements are presented and compared with generator expectations in 7 TeV pp collisions, corresponding to an integrated luminosity of 36 pb^{-1}. In addition, first measurement of jet shapes in heavy-ion (PbPb) collisions are presented and compared with observations in 2.76 TeV pp collisions to probe if the jet structure is modified in the medium due to parton energy loss. The PbPb data set collected in 2011 is analyzed, corresponding to an integrated luminosity of 129 μb^{-1}. The jets are reconstructed with the anti-kT clustering algorithm by utilizing particle-flow objects.

1. Introduction

The jet transverse momentum profile (shape) [1, 2] is sensitive to multiple parton emissions from the primary outgoing parton and provides a powerful test of the parton showering approximation of quantum chromodynamics (QCD), the theory of strong interactions. Previously, jet shapes have been measured in pp collisions at the LHC [3, 4], in $p\overline{p}$ collisions at the Tevatron [5], and in ep collisions at HERA [6]. However, so far measurements of jet shapes have never been performed in heavy ion collisions.

Unlike in pp collisions, high transverse momentum partons produced in heavy ion collisions are expected to lose energy while traversing the hot and dense medium created in these collisions [7]. At RHIC, indirect measurements of energy loss in the medium ("jet quenching") have been made by studying high momentum jet fragmentation products [8]. More recently, the Compact Muon Solenoid (CMS) [9] detector has been used to search for partonic energy loss in the quark-gluon plasma with leading particle [10] and jet coincidence measurements [11].

In this note we present a new measurement to test the effects of the medium using jet shapes. The jet shapes are a sensitive tool for the characterization of the parton-medium interactions by utilizing the energy flow inside the jet. Predictions have been made that the jet shapes will become wider due to quenching effects [12]. In this document we present the first experimental test of this theory.

2. Data analysis and results

In the results presented here jets are reconstructed using the anti-k_t jet clustering algorithm [13], with a resolution parameter R=0.7 for pp collisions at 7 TeV, and R=0.3 for PbPb and pp col-

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lisions at 2.76 TeV. Individually calibrated particle candidates are used as inputs to the jet clustering algorithm. These particle candidates are reconstructed using the CMS particle flow (PF) algorithm [14]. The jet shape is defined as the average fraction of the jet transverse momentum within a cone of a given size r around the jet axis. The jet shapes can be studied by using an integrated or a differential distribution. The differential jet shape $\rho(r)$ is defined as the average fraction of the transverse momentum contained inside an annulus of an inner radius $r_a = r - \delta r/2$ and an outer radius $r_b = r + \delta r/2$, while the integrated jet shape $\Psi(r)$ is defined as the average fraction of the transverse momentum of particles inside a cone of radius r around the jet axis:

$$\rho(r) = \frac{1}{\delta r} \frac{\sum\limits_{r_a < r_i < r_b} p_{T,i}}{\sum\limits_{r_i < R} p_{T,i}}, \qquad \Psi(r) = \frac{\sum\limits_{r_i < r} p_{T,i}}{\sum\limits_{r_i < R} p_{T,i}}, \tag{1}$$

where δr is used as the annulus size, which is 0.1 and 0.05 for 7 TeV and 2.76 TeV collisions, respectively.

Previously, we studied the jet shapes at CMS in 7 TeV pp collisions using a large cone size in order to contain most of the parton energy. The observed detector-level jet shapes and true particle-level jet shapes differ mainly due to jet energy resolution effects. The data are unfolded to the particle level using bin-by-bin corrections derived from the CMS simulation based on the PYTHIA 6.4 [15] Monte Carlo generator which is tuned to the CMS data. The correction factors are determined as functions of r for each jet p_T and rapidity bin and vary between 0 and 20%. These unfolding factors depend on the MC model, since the model affects the momentum and angular distributions, as well as the flavour composition of the particles in the jets, and therefore the simulated detector response to the jet. The systematic uncertainties include contributions from the choice of the fragmentation model, the individual particle calibrations, and the uncertainties in the determination of the jet energy scale. The differential jet shape measurements for jets produced at midrapidity ($|y| < 1$) for representative bin in jet p_T, along with their statistical and systematic uncertainties, compared with predictions from different MC generators and tunes are presented in Fig. 1 in the left panel. Larger values of $\rho(r)$ denote larger transverse momentum fraction in a particular annulus. At high jet p_T, the data are peaked at low radius r, indicating that the jets are highly collimated with most of their p_T concentrated close to the jet axis, while they widen at lower jet p_T. For the lowest jet p_T bins, the p_T distribution within the jet flattens considerably. In order to investigate the jet p_T dependence of the jet shapes, we determined out-of-cone energy outside a cone of size r=0.3 (1-$\psi(r = 0.3)$) as a function of jet p_T for jets produced at midrapidity. This is illustrated in Fig. 1 in the right panel. As depicted in Fig. 1, at low jet p_T the PYTHIA8 [16] generator predicts somewhat narrower jets than those found in data, while PYTHIA6 tune D6T predicts wider jets. PYTHIA6 Tune Z2 provides a good description of data at low jet p_T. At jet $p_T > 40$ GeV/c the PERUGIA2010 [17] and D6T tunes describe the data better than tune Z2. HERWIG++ [18] predicts wider jets than observed in data over most of the jet p_T region except at the forward rapidity regions where the agreement is better.

We also performed jet shapes studies in heavy-ion collisions in the CMS experiment at 2.76 TeV using inclusive jets with p_T >100 GeV/c within $0.3 < |\eta| < 2$. Due to the difficulty of jet reconstruction in the high multiplicity PbPb environment, and to suppress the underlying-event contribution, jet reconstruction was done with a small cone size (R=0.3). All charged particles that pass a $p_T > 1$ GeV/c threshold are used to reconstruct jet shapes. Corrections for the tracking inefficiency are applied. The hot-and-dense medium is expected to modify a measured jet shape in two ways. First, the partons that fragment into jets interact with the medium directly.

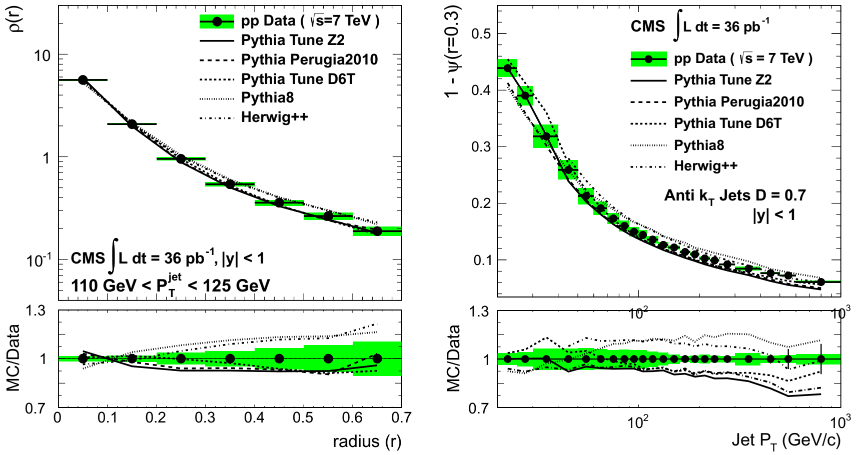

Figure 1: Left figure shows differential jet shape for central jets ($|y| < 1$) for a representative jet p_T bin. The figure on the right shows measured integrated jet shapes, $1 - \psi(\mathrm{r} = 0.3)$, as a function of jet p_T in the central rapidity region $|y| < 1$. The data are compared to particle-level predictions with various tunes for both differential and integrated jet shapes. Statistical uncertainties are shown as error bars on the data points and the shaded region represents the total systematic uncertainty of the measurement.

Secondly, the soft particle production from the underlying event adds many extra particles to the jet, predominantly at low momenta. This second effect produces a background that must be removed. In order to subtract the heavy-ion background, an η-reflection technique [19] was used. The background shape distribution is subtracted from the obtained jet shape distribution. In order to understand the medium-parton interactions we compare the PbPb jet shapes results with those obtained from pp a reference. For a direct comparison between pp and PbPb collisions, the jet momentum resolution deterioration in PbPb events is taken into account. For this purpose, the reconstructed p_T of every jet in the pp data is smeared by the quadratic difference of the jet energy resolution obtained in PbPb and pp. In order to keep the same jet energy scaling in pp and PbPb, a reweighting factor, calculated from the ratio of the PbPb to pp smeared distribution, is applied to the pp jet p_T after smearing. The smeared and reweighted pp jet p_T distribution matches with PbPb jet p_T spectra in each centrality bin of this analysis, which allows us to perform a direct comparison of pp and PbPb jet shapes.

The measured differential jet shapes for PbPb and pp reference data are presented in Fig. 2 for different centrality bins, ranging from most-peripheral 50–100% to most central 0–10%. The bottom panel shows the ratio of the PbPb jet shapes to the jet shapes for a pp reference obtained for the respective selections. This comparison is important for quantifying the modification of the jet structure in the medium by examining deviations from unity in the jet-shape ratios. The ratios are close to unity for peripheral and mid-peripheral collisions (50-100% and 30-50%), and show a rising trend towards large radius r for mid-central and most central collisions (10–30% and 0–10%). For r>0.25, a PbPb/pp jet shape ratio of 1.38 ± 0.10 (syst.) is observed, indicating a moderate, but significant modification of the jet structure in the most central heavy-ion collisions.

3. Summary

We have presented measurements of jet shapes in proton-proton collisions at a centre-of-mass energy of 7 TeV, collected by the CMS detector at the LHC. Jets become narrower with increasing jet p_T predicted by various QCD Monte Carlo models. The measurements may be used to further improve these Monte Carlo models.

Measured jet shapes in PbPb collisions show a significant modification of the jet shapes in central collisions is observed. This modification is consistent with expectations from jet quench-

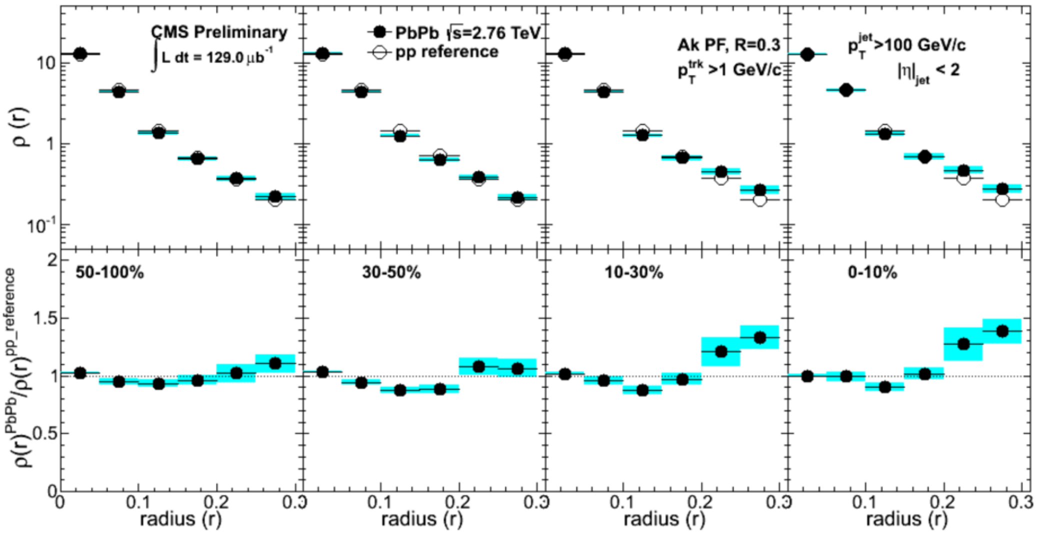

Figure 2: Differential jet shapes in PbPb and pp collisions are presented for different centrality bins for $p_T^{Jet} > 100$ GeV with track $p_T > 1$ GeV (top panels). Results from data are shown as black points while the open circles show the reference pp. In the bottom row, the ratio of the PbPb and pp jet shapes is shown. The blue band shows the total systematic while the error bars indicate the statistical errors.

ing models in heavy-ion collisions.

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